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27. Long-Term Durability of Composites

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Contents:

Key Words*: Constant strain rate (CSR), Creep, Fatigue, Master curve, Time-temperature superposition principle, Carbon fiber reinforced polymer (CFRP) composite*

1. Summary

Prof. Miyano's group at Kanazawa Institute of Technology (KIT) has proposed an accelerating testing methodology for assessing long-term mechanical performance of carbon fiber reinforced polymer (CFRP) composites. The methodology is composed of constructing the master curve for several deformation modes based on four hypotheses:

(A) Same failure mechanisms of CFRP composites under constant strain rate (CSR), creep and cyclic loading over the same time and temperature, which is controlled by the viscoelastic instability of polymer resins
(B) Same time-temperature superimposition principle for all the failure modes
(C) Linear cumulative damage law for monotonic loading
(D) Linear dependence of fatigue strength under various stress ratios ($R_s = \sigma_{min}/\sigma_{max}$)

The validity of hypotheses (A) and (B) has been experimentally proven in a number of CFRP systems by several investigators. The master curves for CSR, creep (constant loading) and fatigue tests are constructed by applying the time-temperature superposition principle. The variations of the CSR strength (σ_s), creep strength (σ_c) and fatigue strength (σ_f) to the time to failure (t_s, t_c and t_f) is shifted by the time-temperature shift factor [$a_{To}(T)$] given in Eq. 1, which is independent of the loading modes.

$$a_{To}(T) = \exp[\Delta H/2.3R(1/T - 1/T_o)] \qquad (1)$$

where R is the gas constant and T_o is the reference temperature. The value of ΔH for the CFRP failure and storage modulus of the polymer resin are found to be identical due to the failure mechanism of CFRP composites controlled by the viscoelastic flow of polymer resins (Fig. 1). To determine the master curves [$\sigma_s(t_s'$: $T_o)$, $\sigma_c(t_c'$: $T_o)$ & $\sigma_f(t_f'$: R_s, f, $T_o)$], the reduced failure time (t_s', t_c' and t_f') is defined by

$$t_s' = t_s/a_{To}(T) \qquad \text{for CSR} \qquad (2a)$$

$$t_c' = t_c/a_{To}(T) \qquad \text{for creep} \qquad (2b)$$

$$t_f' = t_f/a_{To}(T) = N_f/f\,a_{To}(T) = N_f/f' \qquad \text{for fatigue} \qquad (2c)$$

where N_f is the number of cycles to failure and f is the frequency of cyclic loading. The master curve can be applied in a wide temperature range above and below the glass transition temperature though ΔH becomes different depending on the polymer structure (Fig. 1). For the CSR tests, the variations of σ_s to t_s are measured under various loading rates and temperatures. For the creep test, t_c is determined as a function of constant σ_c at various temperatures. Different cumulative damage proceeds in CFRP composites subjected to rising (CSR) and constant (creep) loading. In order to estimate t_c from the CSR tests, linear cumulative damage for monotonic loading approximated by stepwise one (see Fig. 2) is defined by

$$\int_0^{t^*} dt/t_c[\sigma(t)] = \sum_i^{2n-1} \Delta t/t_c[\sigma_i(t)] = [t_s(\sigma_{2n})/n][1/t_c(\sigma_1) + \cdots + 1/t_c(\sigma_{2n-1})] = 1 \qquad (3)$$

where t^* [$= t_s(\sigma_{2n})$] is the failure time under stress history, Δt ($= t^*/n$) is the time interval for stepwise loading and $t_c[\sigma_i(t)]$ is the creep failure time under $\sigma_i(t)$. Thus, $t_c(\sigma_{2n-1})$ can be determined from $t_s(\sigma_{2n-2})$ and $t_s(\sigma_{2n})$ using Eq. 4 derived from Eq. 3:

$$t_c(\sigma_{2n-1}) = t_s(\sigma_{2n})\, t_s(\sigma_{2n-2}) / [n\, t_s(\sigma_{2n-2}) - (n-1)\, t_s(\sigma_{2n})] \qquad (4)$$

The linear cumulative damage law for the loading history [hypothesis (C)] has been proved by good agreement of the master curves for the CRS and creep observed in many CFRC systems.

In order to construct the fatigue master curve, the value of t_f is converted from N_f using f and t_f' is defined by the shifted frequency (f') (Eq. 2c). Moreover, changing f and R_s as well as temperatures affects the relationships of σ_f to t_f'. By applying a linear dependence of the fatigue strength on R_s [hypothesis (D)], the fatigue master curve [σ_f (t_f: R_s, f, T)] for the various R_s is estimated by

$$\sigma_f\,(t_f{:}\ R_s, f, T) = \sigma_{f:1}(t_f{:}\ f, T)\, R_s + \sigma_{f:0}(t_f{:}\ f, T)(1 - R_s) \qquad (5)$$

where $\sigma_{f:1}$ is the fatigue strength for R_s= 1 and $\sigma_{f:0}$ is the CSR strength (R_s = 0, N_f = 1/2 or t_f =1/2f). As N_f is increased, σ_f drastically decreases when t_f' is relatively short (Fig. 3). The hypothesis (D) is verified by series of fatigue experiments performed under various R_s.

The applicability of the hypotheses (A-D) for several CFRP composite systems is summarized in Table 1. In various GFRP/metal joining systems (conical shaped joint, brittle & ductile adhesive joints and bolted joint), it is possible to construct the master curves as well. Based on KIT's systematic studies, it is unequivocal that the accelerating testing methodology is applicable when polymer resins fracture in a brittle manner and the deformation behavior in carbon fibers is time independent. Moreover, the environmental degradation of CFRP composites can be assessed using the time-temperature-water adsorption superimposition principle.
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Table 1. Applicability of master curve for various CFRP composites subjected to various loading modes

Fiber		Matrix	Type	Fiber/matrix	Loading Mode	Hypothesis			
						A	B	C	D
Carbon	PAN	Epoxy	UD	T400/828	LT	O	O	O	O
				T300/2500	LB	O	O	O	O
					TB	O	O	O	O
			SW	T400/3601	LB	O	O	O	O
		PEEK	UD	T300/PEEK	LB	O	x	x	Δ
					TB	Δ	x	x	x
	Pitch	Epoxy	UD	XN40/25C	LB	O	Δ	x	O
Glass		Epoxy	SW	E-glass/epoxy	LB	O	Δ	O	x
		Vinylester	PW	E-glass/vinylester	LB	O	O	O	x

Type of fibers:
UD: Unidirectional, SW: Strain woven, PW: Plain woven
Loading modes:
LT: Longitudinal tension, LB: Longitudinal bending, TB: transverse bending

2. Background

Profs. Miyano and Kimpara at the KIT are currently involved in the FY02 NICOP *"Long-Term Durability and Damage Tolerance of Innovative Marine Composites."* Master curves are being developed to evaluate the mechanical performance of plain-woven CFRP (T300 & T700/Vinylester resin) marine composites. Prof. Kimpara's group is studying impact damage and residual compressive strength of CFRP laminates using a thermo-elastic stress analyzer and ultrasonic C-scan method.

3. Assessment

The majority of composite studies focus on detailed microcracking processes but not much on the final failure stage. The KIT approach deals with the macroscopic aspects of composite failure affected by several factors, such as various loading modes, temperature, and environment, in a more systematic manner. The accelerated testing methodology is very unique and useful for the performance evaluation, leading to the development of better composite systems.
http://www.onrifo.navy.mil/Reports/2002/DURACOSYS.doc
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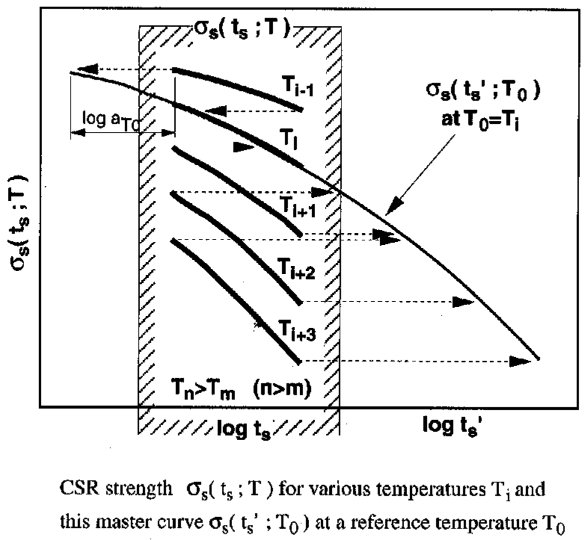

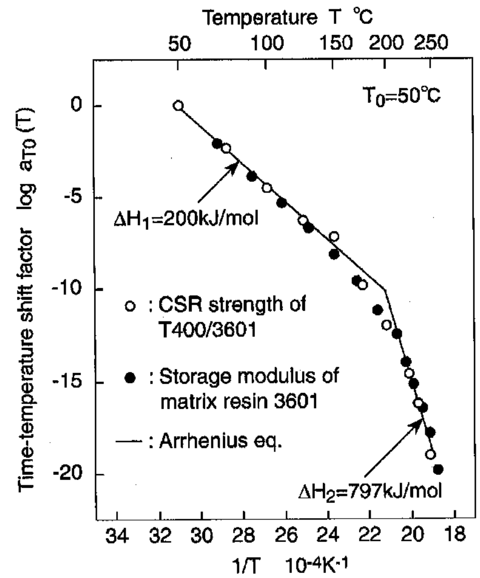

Fig. 1. Time-temperature superposition principle

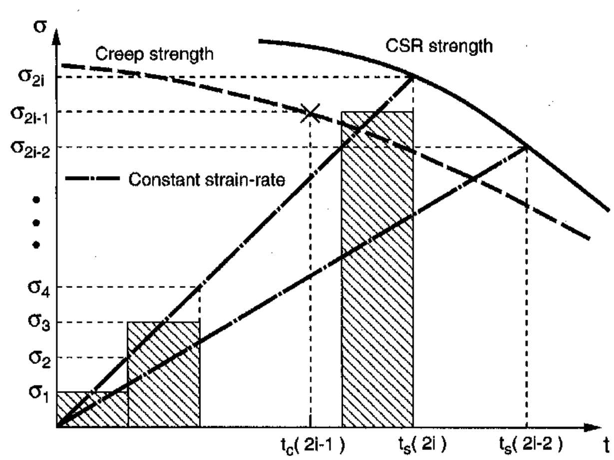

Fig. 2. Construction of creep strength from CSR strength

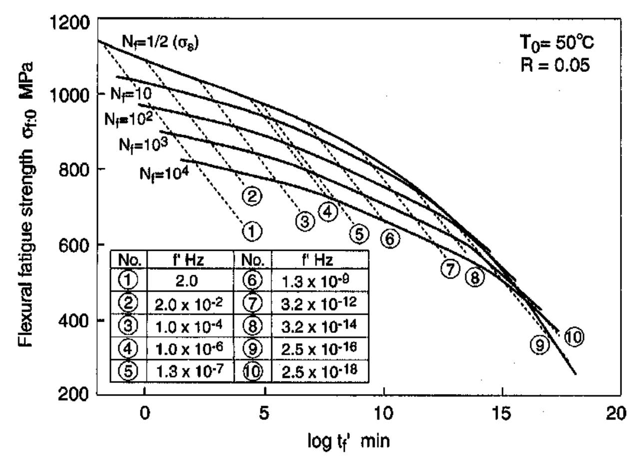

Fig. 3. Master curves of fatigue strength of T400/3601 for R =0.05